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Research on the Potential Fire Behavior and Fuel Control of Pinus yunnanensis var. pygmaea Forest in Central Yunnan

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Abstract

Pinus yunnanensis forest is the most important forest type in southwest China and also the largest existing forest type in Yunnan Province. As a variety of Pinus yunnanensis,pinus yunnanensis var. pygmaea has stable characteristics and important value in ecological protection and pine pollen collection. When a fire breaks out in pinus yunnanensis var. pygmaea forest, the surface combustible materials release a lot of heat, which is easy to develop into a medium to high intensity fire and extremely difficult to fight. This paper aims to use FARSITE software and survey data of pinus yunnanensis var. pygmaea forest in central Yunnan to analyze and simulate the characteristics of its potential fire behavior, and take effective measures to control the combustible materials in the forest with comprehensive consideration of its environmental factors and its own potential fire behavior.

Keywords

Forest fire prevention；pinus yunnanensis var. pygmaea forest；FARSITE software；fuel control.

1. Preface

Central Yunnan refers to the four cities of Kunming, Qujing, Chuxiong and Yuxi, which are located in central Yunnan. Central Yunnan is part of the highland basin of eastern Yunnan, dominated by mountainous and inter-mountainous basin terrain, with large differences in elevation, complex and diverse landscapes, and marked vertical and horizontal differences in climate. The complex geography and unique climatic conditions make the ecological environment of central Yunnan unique. Therefore, the conservation of forest resources and biodiversity in central Yunnan is of great and far-reaching practical and historical significance. Yunnan is the most prone and hardest hit area for forest fires in the country, and the central Yunnan region is the key forest fire risk area in Yunnan Province, where strengthening forest fire warning and combustible material regulation are the main measures. The pinus yunnanensis var. pygmaea is a variety of the Yunnan pine， it is the result of frequent fire, logging and grazing and the special environmental conditions of aridity and barrenness, growing in areas from 2200 to 3100m above sea level, often forming alpine dwarf forests or thickets on dry, barren sunny slopes. In the subtropical mountain plains of central and southeastern Yunnan, pinus yunnanensis var. pygmaea as a pioneer plant community can increase vegetation cover, maintain soil and water, and improve the environment under adverse conditions. At the same time, the combustible material in its forest has high energy, and it is difficult to put out a fire. In 2010, the "2-7" forest fire in Shilin, Kunming, the vegetation was mainly pinus yunnanensis var. pygmaea. In 2014, the forest fire in Anning, Kunming, was mainly covered with pinus yunnanensis var. pygmaea. It can be seen that pinus yunnanensis var. pygmaea forest, as one of the fire vegetation types in forest fires in central Yunnan, is of great significance for the prevention, control and fighting of forest fires in central Yunnan to understand its potential fire behavior in depth.

2. Current status of domestic and international research

The Missoula Fire Science Laboratory in the United States has developed the FARSITE (Fire Area Simulator) model to study the fire behavior of forest combustibles under different environmental and combustible conditions. The model is based on Geographic Information System (GIS) and uses terrain data, combustible material data, and meteorological data to build a two-dimensional model to simulate the fire behavior under surface fire, canopy fire, flying fire, and changes in water content of combustible material, and the model has received many research experiments by scholars at the beginning of its development. Ross J. Phillips et al. used the FARSITE model to assess the effects of different combustibles on fire behavior in the southern Appalachians, and Williams et al. used the FARSITE forest fire spread model in conjunction with the landscape simulation software VNS to simulate a major forest fire event that occurred in Minnesota in 1894 in the United States. Roghayeh Jahdi et al. simulated forest fires in northern Iranian forests during the summer and autumn of 2010 by FARSITE and assessed the effect of climatic conditions on simulation accuracy. Some foreign scholars have applied FARSITE to the study of shrubland fire behavior. Weise et al. concluded through mutual validation of combustion experiments and model simulations that the use of the FARSITE standard combustible model FM4 would overestimate the actual fire spread of shrub vegetation, demonstrating that the accuracy of the simulations can be improved by developing and using a custom combustible model. Kim et al. used the FARSITE model to simulate the effects of four spatial patterns of combustible material handling (random, scattered, aggregated, and regular distribution) on forest fire risk in northeastern Oregon, USA, and showed that scientific combustible material handling patterns are effective in reducing forest fire risk. Keeley et al. used the FARSITE model, a custom combustible model and input meteorological data from the Mediterranean region to simulate a brush fire occurring in the Mediterranean region three times and analyzed the accuracy of the results, concluding that the custom combustible model CM28 was closer to the real burning data. Arca et al. evaluated the accuracy of the FARSITE model in predicting fire spread and forest fire behavior in Mediterranean vegetation and its influencing factors, and predicted the spatial distribution of potential forest fire occurrence probabilities in Mediterranean vegetation under different meteorological and topographical conditions.

The domestic research on fire behavior simulation using FARSITE model started late, and Tian et al. analyzed the main features, application limitations and future development directions of FARSITE. Wu et al. developed a theoretical application study of the FARSITE model and applied it to analyze the potential fire behavior of forest areas in Fenglin Nature Reserve, and Nashuntaogtao et al. used the FARSITE software to analyze the simulation of forest fire spread under different initial combustible material water content, different wind speed conditions, and different slope orientation conditions. Liyu Tang et al. developed a prototype forest fire spread 3D visualization simulation software system using FARSITE's forest fire spread simulation engine and a 3D visualization method of forest fire based on particle system. It can be seen that the domestic research on fire behavior using FARSITE has achieved good results, but the research objects are mostly arbor forests. The combustion fire behavior and its potential energy of the surface combustible material in the pinus yunnanensis var. pygmaea were studied by Qiuhua Wang et al. The surface combustible material load is large and has great combustion energy. Zhang Huihong compared the natural regeneration ability of pinus yunnanensis var. pygmaea after fire in different environments and concluded that pinus yunnanensis var. pygmaea has a strong regeneration ability to sprout new branches very quickly after fire. Shen Huajie et al. studied the burning characteristics of young stands of pinus yunnanensis var. pygmaea on fire trails and pointed out that more attention should be paid to prevent the occurrence of rekindling when extinguishing. Pinus yunnanensis var. pygmaea forest is a unique vegetation type in central Yunnan, and the analysis of its fire behavior is not comprehensive enough in current studies, only a relatively small number of scholars have studied the fire behavior of ground combustible materials in pinus yunnanensis var. pygmaea forest, and the research methods are mostly indoor combustion experiments. Based on the FARSITE model, the actual fire source in the fire area is selected as the ignition point for fire behavior simulation analysis, applying geospatial data and spatio-temporal environmental data, overcoming the shortcomings of traditional static simulation, and more objectively and truly reflecting its fire spread pattern and potential forest fire behavior.

FARSITE software simulation can take effective measures for its combustible regulation, provide valuable reference for its understory plan burning and forest isolation zone construction, provide scientific theoretical basis for forest fire prevention and extinguishing, and reduce the occurrence of forest fires in order to better protect forest resources.

3. FARSITE model fundamentals

3.1. Surface fire subsystem

FARSITE model surface fires were calculated using the Rothermel equation.

$$R = \frac{I_R \zeta(1+\Phi_w+\Phi_s)}{\rho_b \varepsilon Q_{ig}} \tag{1}$$

In the formula: R is the steady-state rate of spread of the fire head(m•min^{-1});$I_R$is the flame zone reaction intensity(kJ•min^{-1} • m^{-2});ζis the spread rate;$\Phi_w$is the wind speed correction factor;Φ_s is the slope correction factor;ρ_b is the density of combustible bed(kg• m^{-3});$\varepsilon$is the effective thermal coefficient;Q_{ig} is the calorific value of combustion(kJ•kg^{-1}).

Surface fire fireline intensity(kW•m^{-1})is another important indicator of fire behavior，The calculation formula is：

$$I_b = \frac{I_R}{60} \times \frac{12.6R}{\sigma} \tag{2}$$

In the formula，$\sigma$is the surface volume ratio of the combustible bed(m^{-1}).

3.2. Forest Crown Fire Subsystem

Forest canopy fire was calculated using the van Wagner equation.The threshold of canopy fire I_o(kW• m^{-1})depends on canopy branch water content M (percentage) and understory height CBH (m), calculated as：

$$I_o = (0.01CBH(460 + 25.9M)^{3/2} \tag{3}$$

UsingI_o and the all-pervasive canopy fire expansion rate RAC as thresholds, forest canopy fires are classified into three categories：

Ⅰ. Passive crown fire: I_b≥I_o, $R_{C\ actual}$＜RAC;

Ⅱ. Active crown fire: I_b≥I_o, $R_{C\ actual}$≥RAC, E＜E_o;

Ⅲ. Independent crown fire: I_b＞I_o， $R_{C\ actual}$≥RAC, E＞E_o.

In the formula: EandE_o are the actual and critical energy values, respectively(kW• m^{-2});RAC is the rate of canopy fire expansion for all-combustion type(m•min^{-1})，The calculation formula is 3.0/CBD;CBD for Lam Guan Yung Heavy(kg • m^{-3});3. 0is the empirically calculated value，That is, the forest canopy flame mass flow rate(0.05kg•m^{-2} • s^{-1})multiplied by the conversion factor(60 s • min^{-1})。

The expansion rate of intermittent canopy fire is calculated to be equivalent to the surface fire rate，The actual rate of expansion of the generalized canopy fire was calculated according to the maximum forest canopy fire rate $R_{C\ max}$(m • min^{-1})：$R_{C\ actual}$=R+CFB($R_{C\ max}$-R)，if $R_{C\ actual}$≥RAC,then$R_{C\ max}$=3.34$R_{10}E_i$，among them，3.34R_{10} is the US combustible model 10 surface expansion velocity R calculated using a wind coefficient of 0.4;E_i is the fraction of the fire expansion speed at the ith fireline vertex(E_i＜0.1);CFB is the specific gravity of forest crown burning.

The forest canopy fire intensityI_c(kW• m^{-1})is modified by the modified surface fire intensity calculation formula, which is given by：

$$I_c = 300(I_b/300R + CFB \bullet CBD(H - CBH))R_{C\ actual} \quad (4)$$

where, H is the tree height (m).

3.3. Fire Acceleration Subsystem

FARSITE defines acceleration as a function of the time required for a forest fire to reach 90% of its new equilibrium velocity from its original velocity. The rate of fire spread at time point t depends entirely on the fastest rate that can be achieved under the existing burning conditions at time point t. The functional equation is:

$$R_t = R(1 - e^{-a_a t}) \quad (5)$$

where R is the equilibrium expansion speed(m • min^{-1})， t is the combustion time(min)，$a_a$is a constant term.

3.4. Flying Fire Subsystem

A flying fire refers to a new fire starting point formed in front of the main fire head by the action of wind, etc. It can cross obstructions several kilometers away from the existing fire line, while completely changing the fire behavior and fire expansion pattern. FARSITE uses the equation developed by Albini to calculate the fly-fire expansion, which calculates the process from canopy fire to fly-fire. The ash and debris flyover height is determined by the time it takes to drift from its original position and is calculated as：

$$t_f = t_o + 1.2 + \frac{a_x}{3}((\frac{b_x + z/z_F}{a_x})^{3/2} - 1) \quad (6)$$

z is the height of the object(m);$z_F$is the flame height(m);a_x=5.963;b_x=4.563;$t_f = t_0 + t_1 + t_2 + t_3$; $t_0$is the time for the canopy to burn steadily;$t_1$is the time it takes for the embers to transfer from the initial height to the end of the flame， The calculation formula is：

$$t_1 = 1 - (z_0/z_F)^{1/2} + \frac{v_0}{w_F}\ln(\frac{1 - v_0/w_F}{(z_0/z_F)^{1/2} - v_0/w_F}) \quad (7)$$

$t_2$is the time taken by the residual ash to traverse the spreading zone and is calculated as:

$$t_2 = 0.2 + B(\frac{D_p}{z_F})^{1/2}(1 + B(\frac{D_p}{z_F})^{1/2})\ ln(1 + 1/(1 - \frac{D_p}{z_F})^{1/2}))) \quad (8)$$

t_3 is the time of residual ash drift, calculated as:

$$t_3 = \frac{a_x}{0.8v_0/w_F}(ln\ (\frac{1 - 0.8v_0/w_F}{1 - 0.8rv_0/w_F}) - 0.8(v_0/w_F)(r - 1) - \frac{1}{2}(0.8v_0/w_F)^2(r - 1)^2) \quad (9)$$

In the formula , v_0 extreme speed(m • s^{-1})， w_F flame speed(m • s^{-1})， $r = ((b + z/z_F)/a)^{1/2}$, D_p is the diameter of the object(m)，B=40，v_0=$w_F/B(D/z_F)/a)^{1/2}$。

4. Establishment of a FARSITE model of the central Yunnan ground pine forest

4.1. Parameterize landscape features and create landscape element files

Acquisition of vegetation thematic map: Initial classification of vegetation types in WordView-2 remote sensing images of central Yunnan in ENVI software, further manual decompression and topological data processing in GIS to generate a thematic map of Pinus radiata forest in central Yunnan, parameterization of terrain features: GIS software as technical support, based on DEM digital elevation model (30 m×30 m) to generate a map of elevation, slope and slope direction in central Yunnan. The elevation is mainly used to simulate the spatial variation of temperature and humidity at different elevation gradients, and the slope and slope direction mainly simulate the change of fire spread rate.

Raster theme	Uses / Description
Altitude	Simulate the spatial distribution of temperature and humidity across the landscape
Slope	Calculating the directional effect of fire expansion; Determining the solar radiation efficiency; Adjusting the rate and direction of forest fire expansion
Slope direction	Co-action with slope
Combustible model	Characteristic parameters of surface combustibles are provided, mainly including dead combustible load at different time lags, live combustible load, combustible surface volume ratio and combustible bed thickness. The combustibles model can be customized or the system's preset model can be used
Canopy coverage	Determine the average shading of surface combustibles, which mainly affects the calculation of surface combustible moisture; aids in the calculation of wind mitigation factors

4.2. Combustible model established

Sample squares were set up in typical sample plots for investigating dead combustible material on the ground and live forest trees. The dominant species, number of plants, cover and height in the sample square were counted. The above-ground parts of the ground pine in the sample square were summarized by organ and weighed separately to record the species, tree height and ground diameter, and different organs of the above-ground parts were weighed fresh and sampled and bagged, and samples of each organ were collected by species, weighed wet and brought back to the laboratory. The respective thicknesses of the undecomposed and decomposed layers were measured, and the surface dead combustible and semi-decomposed materials with different time lags were collected, weighed in the field and sampled and bagged. Combustible classification standards： 1h when the hysteresis combustible material is D≤0.64cm of twigs, leaves and dead weeds;The combustible material at 10h is 0.64cm＜D≤2.54cm twigs;The stagnant combustible material at 100h is 2.54cm＜D≤7.62cmthick branches. All were weighed fresh weight using the full receipt method, and each party took a stratified sample and weighed it and brought it back to the laboratory. For long-term observation sampling.

Indoor sample flammability value index determination method：a、Determination of water content and combustible load： The collected samples were weighed in the field and brought back in bags, and then the samples were put into the oven and dried continuously at 105℃ for 24h to the absolute dry mass, and weighed with an electronic balance to calculate the moisture content of the samples and different time-lag combustibles in the sample, and then deduce the load of each type of combustible material in the sample.b、Calorific value determination： The samples to be measured were dried to constant weight, then the dry mass samples were crushed into powder and sieved, 1.0g of the sieved powder was weighed and pressed into tablets, and the calorific value content of the samples was measured by XRY-1C oxygen bomb calorimeter (each sample was repeatedly measured 5 times and the average value was taken).

Based on the vegetation thematic map and field research to classify the area into different combustible types, the combustible model is composed of various combustible types, and it is necessary to investigate the combustible load, water content, bed thickness, and calorific value of typical vegetation types in different types of areas, and use the survey results as input for the physical and chemical properties of combustible types.

4.3. Forest fire spread simulation

Combining small class survey data and combustible material model, based on DEM data, vegetation cover data, establishing landscape element files under GIS, using FARSITE software, selecting high fire source area as the fire point, setting the simulation time step, spatial distance and forest fire boundary resolution, start and end time, deriving the overfire area under simulated burning conditions, and repeatedly adjusting the model parameters, the model is the final ground Pine forest combustible material model.

4.4. Establishing the spatial distribution of potential fire behavior in shrublands in central Yunnan

In the model of ground pine forest combustible material in the simulation range set a number of fire points near the road, change the environmental parameters for potential fire behavior simulation, potential fire behavior output results include: fire line spread speed, fire area, fire spread boundary, fire line intensity, flame height, the model of each raster points affected by the fire value frequency as potential fire behavior division data, and finally use each GIS Finally, the fire behavior information received by each raster in the GIS is used to cluster them and form a potential fire behavior distribution pattern.

5. Combustible regulation study

5.1. Construction of isolation zones

The distribution pattern of potential fire behavior simulated by the FARSITE software can divide the ground pine forest into zones based on its propagation rate, fireline intensity, heat release, flame length, and other schematics to ensure that the fire is kept under control and damage is minimized when it occurs.

5.2. Reduction of surface combustible loadings

Based on the simulated potential fire behavior of the ground pine forest, the areas with high combustible material load, prone to fire and capable of developing into medium to high-intensity fire when fire occurs are regularly manually picked up for surface combustible material to reduce the probability of forest fire and fire intensity.

5.3. Biological fire protection

Fire prevention forest belt construction is the main direction of biological fire prevention, because it can reduce forest flammability and inhibit the spread of forest fires. China has taken the construction of biological fire prevention forest belt project and the implementation of green fire prevention as a strategic measure to prevent the spread of forest fires, reduce the loss and harm of forest fires, and promote the long-term stability of forest resources. Using the geographical data of the ground pine forest, extracting the distribution of roads, mountains, topography, and other natural conditions and the comprehensive factors of the ground pine forest combustible material situation, fire behavior, geography and natural conditions, we determine the spatial layout of the ridge fire prevention forest belt, fire prevention highway fire prevention forest belt and forest edge fire prevention forest belt and select the corresponding tree species as afforestation species to reduce the fire risk level of the ground pine forest through its own fire resistance and fire prevention ability. Biological fire prevention is a powerful measure to consolidate afforestation and greening achievements, prevent and control mountain fires, and is a strategic system project to guarantee ecological security, with broad development prospects and advantages.

6. Conclusion

China has made certain achievements in potential fire behavior research, but comparative analysis of numerous literature can find that the experimental results are mostly reflected in the form of data information, which is not intuitive and difficult to fully meet the practical needs of forest fire management, while the FARESITE model combines GIS and forest fire spread model, the addition of GIS makes predicting the characteristics of forest fire occurrence more intuitive, fire spread, topography, combustible material conditions can be observed from a two-dimensional or three-dimensional perspective, and can output images for easy maintenance and viewing at any time. The GIS model makes the prediction of forest fires more intuitive, and the fire spread, topography, and combustible material can be observed from two-dimensional or three-dimensional perspectives, and the images can be exported for easy maintenance and viewing at any time, overcoming the shortcomings of traditional static simulation, which can objectively and truly reflect the fire spread and potential forest fire behavior, and provide a scientific basis for spatial zoning of forest fire behavior.

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